

Vapor Compression Heat Pump Cycle with Desorber/Absorber Heat Exchange

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Abstract

In this paper, a special version of a vapor compression heat pump cycle with solution circuit is introduced. In this cycle, the gliding temperature intervals are deliberately chosen so large, that the highest temperature in the desorber (evaporator) is higher than the lowest temperature in the absorber (condenser). As a consequence, part of the absorber will be supplying heat to the desorber resulting into an extremely low pressure difference across the compressor, however, increasing the mass flow rate for a given capacity.

Depending on the application, significant increases in the Coefficient of Performance are available while pressure ratios stay below 2 for all applications discussed here.

Introduction

Since about 60 years, so called 'heat pump cycles with solution circuits' are known in the literature, but only recently a new interest arose leading to

experimental investigations, a pilot plant and a more comprehensive theoretical assessment of these cycles (1-5).

Heat pumps with solution circuits are versions of the rankine cycle which employ working fluid mixtures rather than pure components and in the most general case, the evaporation of the mixture is not complete, rather, a part of the fluid leaving the evaporator is in the liquid state. This liquid is recirculated to the condenser by means of a pump and a separate liquid line. A more detailed description is given in the next chapter.

There are three major advantages these heat pump cycles do provide:

- increased COP due to gliding temperatures in evaporator and condenser, which can be adjusted over a wide range,
- capacity control by merely adjusting the composition of the circulating fluid,
- in two stage versions, reduction of the pressure ratio to typically 45% compared to pure fluids for a given temperature lift (6).

The last point results into a major increase in temperature lift that can be achieved by a single stage compressor, and in higher volumetric efficiencies of reciprocal compressors. In this paper a new modification of heat pump cycles with solution circuits employing condenser/evaporator heat exchange is introduced. This heat exchange decreases the pressure ratio even more

drastically than for common two-stage cycles as shown by an example later. However, it should be mentioned that in all cases any decrease in pressure ratio is traded in for an increase in mass flow rate as required by thermodynamics (6).

The Rankine Cycle with One Stage Solution Circuit

The main difference between the conventional Rankine Cycle for heat pumping and the one employed here is the fact that a mixture of working fluids is used rather than a pure working fluid.

By introducing a mixture two important features are accomplished: First, although evaporation and condensation occur still at constant pressure, the saturation temperature is not longer constant but varies with the composition change of the liquid and vapor phases which occur during the phase change process. This results in so-called 'gliding temperature intervals.' However, these temperature intervals can be deliberately reduced to an acceptable size or eliminated almost completely, if so desired, when the requirement that all the liquid in the evaporator has to evaporate, is eliminated. The remaining liquid portion is then circulated into the condenser by means of a circulation pump. Figure 1 shows the schematic of such a heat pump cycle in a pressure-temperature diagram, so that the relative location of the heat exchangers is indicative of the temperature and pressure levels prevailing. As in a conventional heat pump, there are the four main components: evaporator, compressor, condenser, and expansion device. But in addition a second liquid line with a pump is provided, circulating the liquid remaining in the evaporator into the condenser. Since now two liquid streams are available,

one from the condenser to the evaporator and one from the evaporator to the condenser, it is advisable to bring them into heat exchange for better performance of the cycle. A more detailed consideration of this cycle reveals that the evaporator is converted into a desorber and the condenser into an absorber, components which are commonly thought of being reserved for absorption heat pumps only. But here in contrast to absorption heat pumps the main input of availability is in the form of work not heat. A variety of these cycles has recently been discussed in (5).

The second important feature is the following. Changing the overall composition of the mixture circulating in the heat pump results into a change of vapor pressures at a given temperature and therefore in a change of the capacity of the entire unit. This is a direct consequence of the fact that compressors are constant volume flowrate machines.

Both of these features, gliding temperatures and capacity modulation can be used to increase the overall COP. A third feature, which results into a significant decrease of the pressure ratio, by exploiting the gliding temperature differences, is now introduced.

The DAHX-Cycle

Now the Desorber-Absorber-Heat-Exchange Cycle (DAHX) will be explained. When the one-stage cycle of Figure 1 is considered, one may wonder what happens, if, for special operating conditions, the gliding temperature intervals in the desorber and absorber approach each other or even overlap, i.e., when the highest temperature of the desorber becomes higher than the lowest temperature

of the absorber. In this case, part of the absorber is able to supply heat to a part of the desorber resulting into several interesting consequences: The new cycle requires still one solution pump, although it has features of the two-stage cycle, which is internal heat transfer. In this case the heat for desorption is partially supplied by an outside source and partially by the absorber. Once this is accomplished, the absorber may be shifted as shown in Figure 2 to even lower pressures, moving close to the desorber, increasing the temperature interval in which internal heat transfer is occurring, but simultaneously decreasing the pressure ratio enormously. Of course, it must be noted, that by doing so, more and more refrigerant is evaporated due to internal heat transfer and not due to heat supply from an outside source, causing the mass flow rate to increase but the capacity to decrease. The accomplishment is an extremely low pressure ratio.

Due to the requirement, that now only one solution pump is available, in contrast to the two-stage cycle (6), some flexibility with regard to gliding temperatures is lost. The temperature differences in absorber and desorber, depend on the pressure ratio, and cannot be chosen independently of the pressure ratio as it is the case for the single stage cycle. Large pressure ratios result into large gliding temperature intervals and smaller mass flow rates for a given capacity.

In order to assure that the gliding temperature ranges are available to the fullest extent thermodynamically possible, two additional means for heat exchange have to be provided. The solution leaving the solution pump does not enter the absorber directly, but is rather preheated by the absorber to the highest absorber temperature before it is released into the absorber to absorb

vapor, Figure 2. The same heat exchange has to be provided in the desorber as well. Without this heat exchange it would not be selfevident that the absorber and desorber temperatures approach the respective highest or lowest value thermodynamically possible.

Working Fluids

The DAHX Cycle requires a working fluid mixture, the constituents of which must have very different boiling points in order to be able to cover a large temperature range at constant pressure just by composition change. The fluid mixtures which may be proposed are those which are typically used in absorption heat pumps. On the other hand, since we are considering a vapor compression heat pump, a mixture of halogenated hydrocarbons is used here, R13B1 in R113. The difference in boiling points of these two constituents is 105 K.

Calculation Procedure

All calculations are based on an equation of state which has been adapted to accommodate refrigerant mixtures (7). It allows the calculation of all thermodynamic and caloric properties in the liquid, vapor and two phase region with the need for fitting only one parameter to account for mixture effects. Since no other thermodynamic data are available, this parameter is assumed to be 0.03, which is the average of what is found for most halogenated hydrocarbon mixtures for which data are available. The states of all the streams entering and leaving the components according to Figure 2 have been calculated, assuming saturated conditions at desorber and absorber outlets. The efficiency of the solution pump is set to 0.7 and the volumetric

efficiency η of the compressor is calculated according to:

$$\eta = 1 - m\left(\frac{V_s}{V_d} - 1\right) \quad (1)$$

where m is the fraction of the clearance volume to total volume of the cylinder and V_s and V_d are the specific volumes at the suction and discharge side of the compressor, respectively.

Results

The performance of the DAHX Cycle has been evaluated for three cases with the same minimum temperature of 40°C for the heat rejected by the desorber to an outside sink, and the same maximum temperature of 0° for the heat supplied to the absorber from an outside source, but for three different gliding temperature intervals. Then these calculations were repeated to obtain a second set of data for a different maximum temperature of the absorber, 10°, to bracket the range of temperatures encountered in air-conditioning.

Figure 3 shows the two sets of temperature intervals (represented by bars) which are obtained in such desorber and absorber parts, which exchange heat with the heat sink or source while the internal heat exchange is occurring in the gap between two bars. Each set of bars refers to different evaporator temperatures as can be easily recognized from Figure 3. The length of a bar represents the size of the temperature interval (see y-axis in Figure 3) while its location (with regard to y-axis) gives the absolute temperatures. The x-axis shows a composition shift occurring in that part of the absorber, that

rejects heat to the outside. We see that with increasing composition change, the gliding temperature interval increases as well. Since the composition change can be controlled by adjusting the flow rate through the solution pump, the size of the temperature interval can be selected. Figure 4 shows the pressure ratio for the six cases of Figure 3 with the same x-axis. For the cases discussed here, the pressure ratios do not exceed the value of two, while the numbers given in Figure 4 represent as upper limit values obtained for conventional R22 heat pumps, when they have to match the highest and lowest temperatures which are achieved by the DAHX cycle. The enormous difference in pressure ratios is obvious.

Figure 5 shows cooling capacities for the six cases of Figure 3. The conventional R22 system exhibits undoubtedly significantly higher capacities. However, when the capacity for R22 is decreasing because of higher temperature lift requirements, the capacity of the DAHX cycle increases, since less capacity is required for internal heat exchange (thus allowing the pressure ratio to become larger, though slightly compared to R22). Here a situation is faced where we see a trade off between low pressure ratio and low capacity or larger pressure ratios and increased capacity. This behavior is quite contrary to what is experienced with conventional cycles.

Lastly, Figure 6 shows the COP's for the cases of Figure 3. When a large temperature lift is required, the DAHX exhibits COP's which are up to five times higher than R22 cycles due to a better match of heat transfer conditions, but only for applications of course where a temperature change of 35K in the desorber is desired. When the temperature intervals approach a condition commonly seen in R22 cycles, then the COP of R22 is slightly superior,

but nevertheless the pressure ratio of the DAHX cycle is between 1.1 and 1.3, (small Δx , Figure 4).

Technical Implications

The DAHX cycle offers an extremely low pressure ratio opening air conditioning to the application of low cost low pressure head compressors. However, the internal heat transfer area is significantly increased, especially in the extreme cases of very small temperature differences in the outside part of desorber and evaporator. In this case the COP is in a similar range as the one for pure R22 while the pressure ratio is in the range of 1.1 to 1.3. However, the larger the temperature change of the heat sink or heat source fluid, the more heat exchange area and capacity is devoted to heat pumping and the less to internal heat exchange reducing the pressure ratio. In any case, the pressure ratio remains below 2. It is mentioned, that most of the heat exchange area is required for two-phase heat transfer, which is usually small especially when compared to air/refrigerant heat exchangers. In the case of an air conditioner, the overall size of the unit will still be determined by the coils.

Acknowledgments

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Figure Captions

Figure 1 Heat Pump Cycle with single stage solution circuit. The relative location of absorber and desorber is indicative of pressures, temperatures and compositions prevailing in these components (compare to $\ln(p)$, $1/T$ diagram in upper half).

Figure 2 Desorber/Absorber Heat Exchange Cycle superimposed on vapor pressure curves for constituents of mixture.

Figure 3 Temperature intervals in such absorber and desorber parts, which exchange heat with outside sink or source, plotted versus composition change occurring in the high temperature part of the absorber. Desorber/Absorber Heat Exchange occurs in the gap between two bars, as indicated by the connecting dashed line.

Figure 4 Pressure ratio for DAHX cycles and conventional R22 cycles (assuming that latter has to match the same highest and lowest heat sink and source temperatures).

Figure 5 Cooling Capacity for DAHX cycles and R22 cycles.

Figure 6 Coefficient of Performance for DAHX cycles and R22 cycles (assuming the latter have to match the highest and lowest heat sink and source temperatures).

APPENDIX

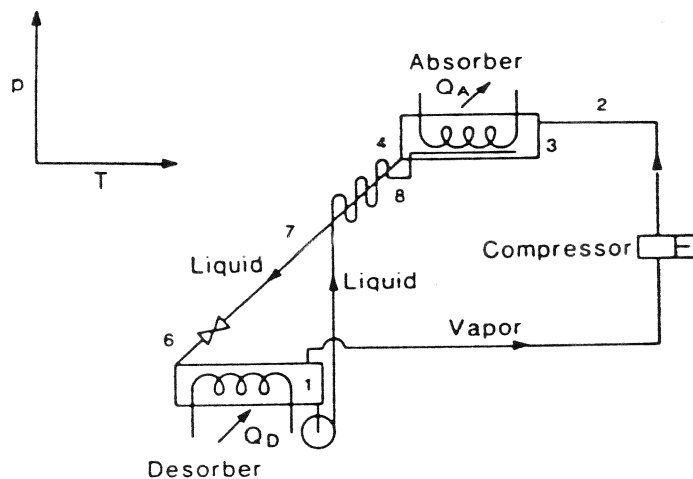


Figure 1. Heat Pump Cycle with single stage solution circuit. The relative location of absorber and desorber is indicative of pressures, temperatures and compositions prevailing in these components.

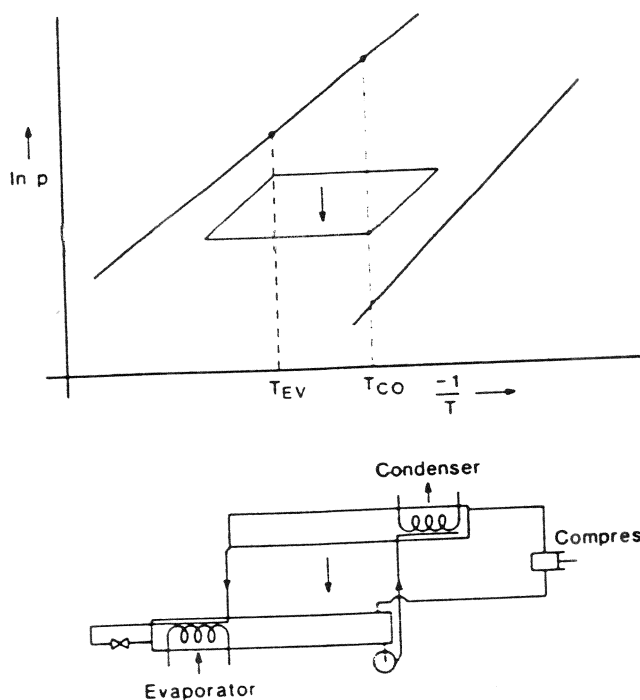


Figure 2. Desorber/Absorber Heat Exchange Cycle superimposed on vapor pressure curves for constituents of mixture.

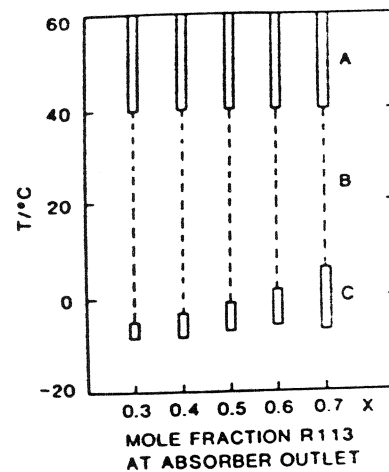


Figure 3. Temperature intervals are plotted vs. composition at absorber outlet. Desorber/Absorber Heat Exchange: B, Heat Rejected A Heat Absorbed C

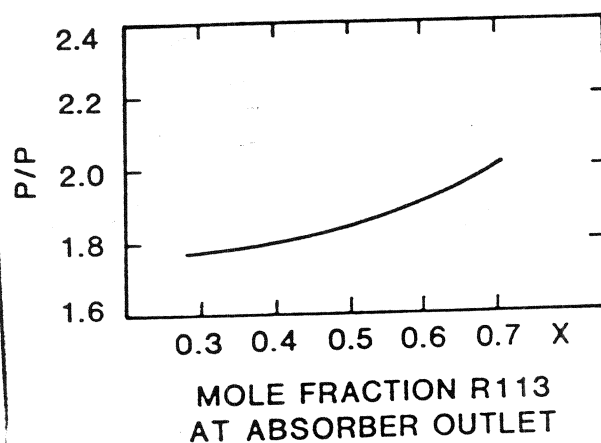


Figure 4. Pressure ratio for the DAHX cycles. The pressure ratio for a conventional R22 system would be 6.76.

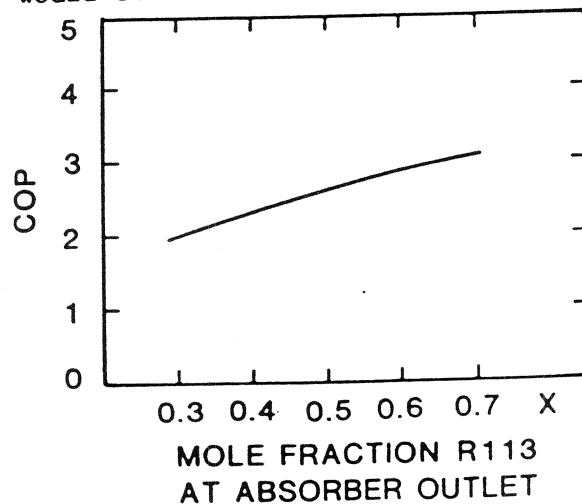


Figure 5. COP for the DAHX cycles. The COP of a conventional R22 cycle would be 1.78.

